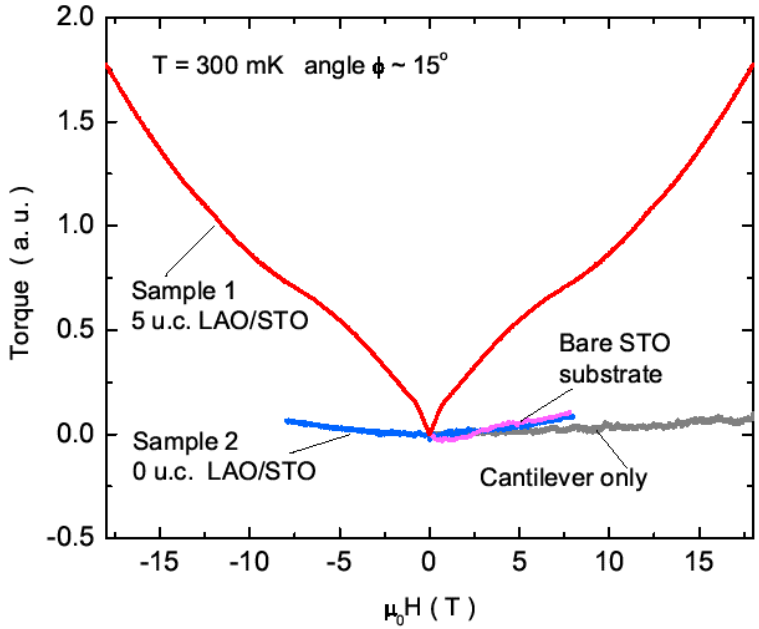
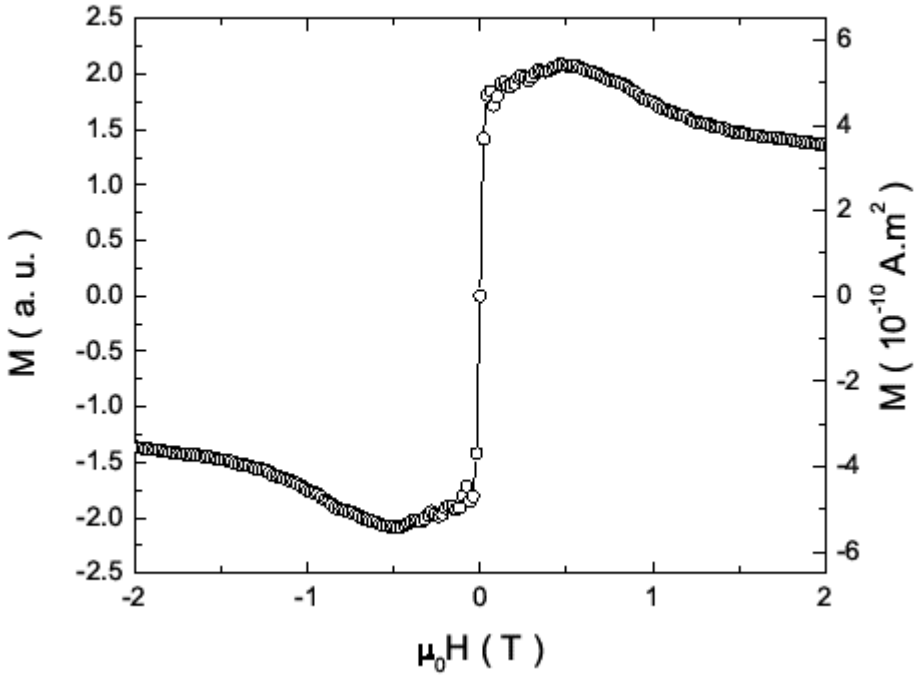
Magnetism of $LaAlO_3/SrTiO_3$ heterostructure

Lu LI
University of Michigan





Acknowledgement

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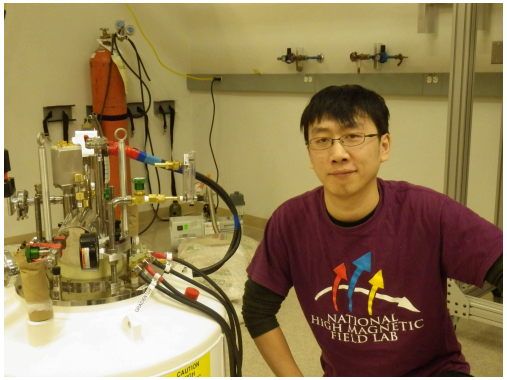
Massachusetts Institute of Technology

Pappalardo Fellowships in Physics

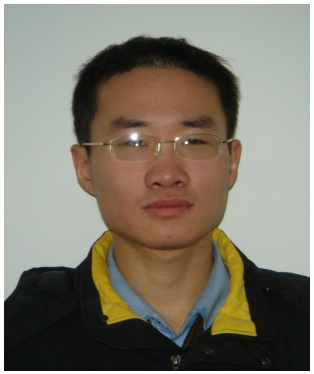
NATIONAL HIGH MAGNETIC FIELD LAB

Acknowledgement

Gang Li



Fan Yu



Ben Lawson

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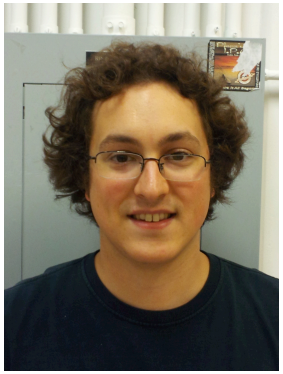

Visiting students

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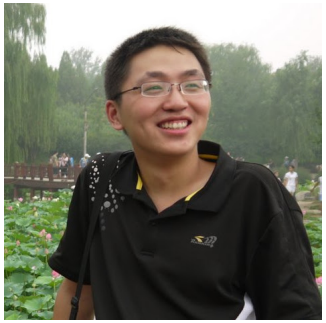


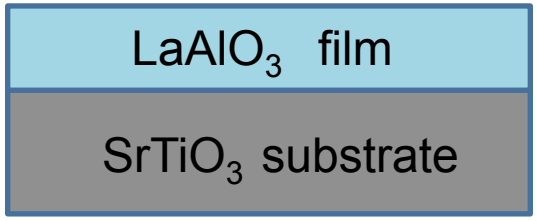
Wudi Wang

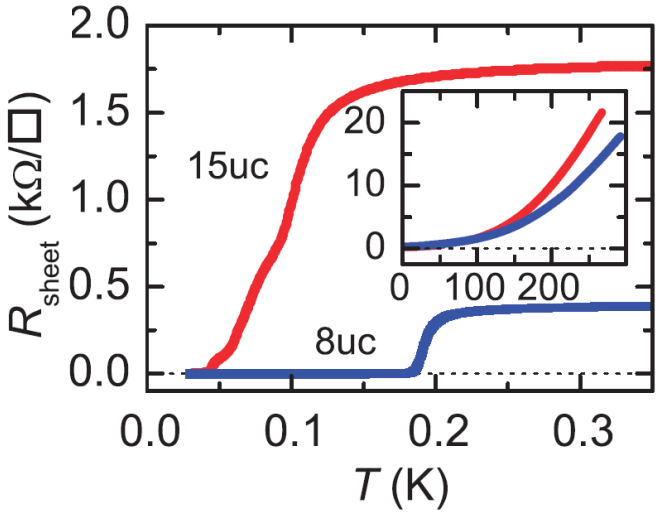
Adam Berkley

Outline

1. **Conductive Interface $LaAlO_3/SrTiO_3$**
   - Mobile charge from polar discontinuity
2. **Magnetization of the $LaAlO_3/SrTiO_3$ single-layered interface**
   - Torque magnetometry
   - Spontaneous magnetic moment
   - Critical thickness of magnetic ordering
   - Thickness dependence of magnetic ordering temperature
   - What happens with γ-$Al_2O_3/SrTiO_3$
   - Coexistence of ferromagnetism and superconductivity

Conductive Interface

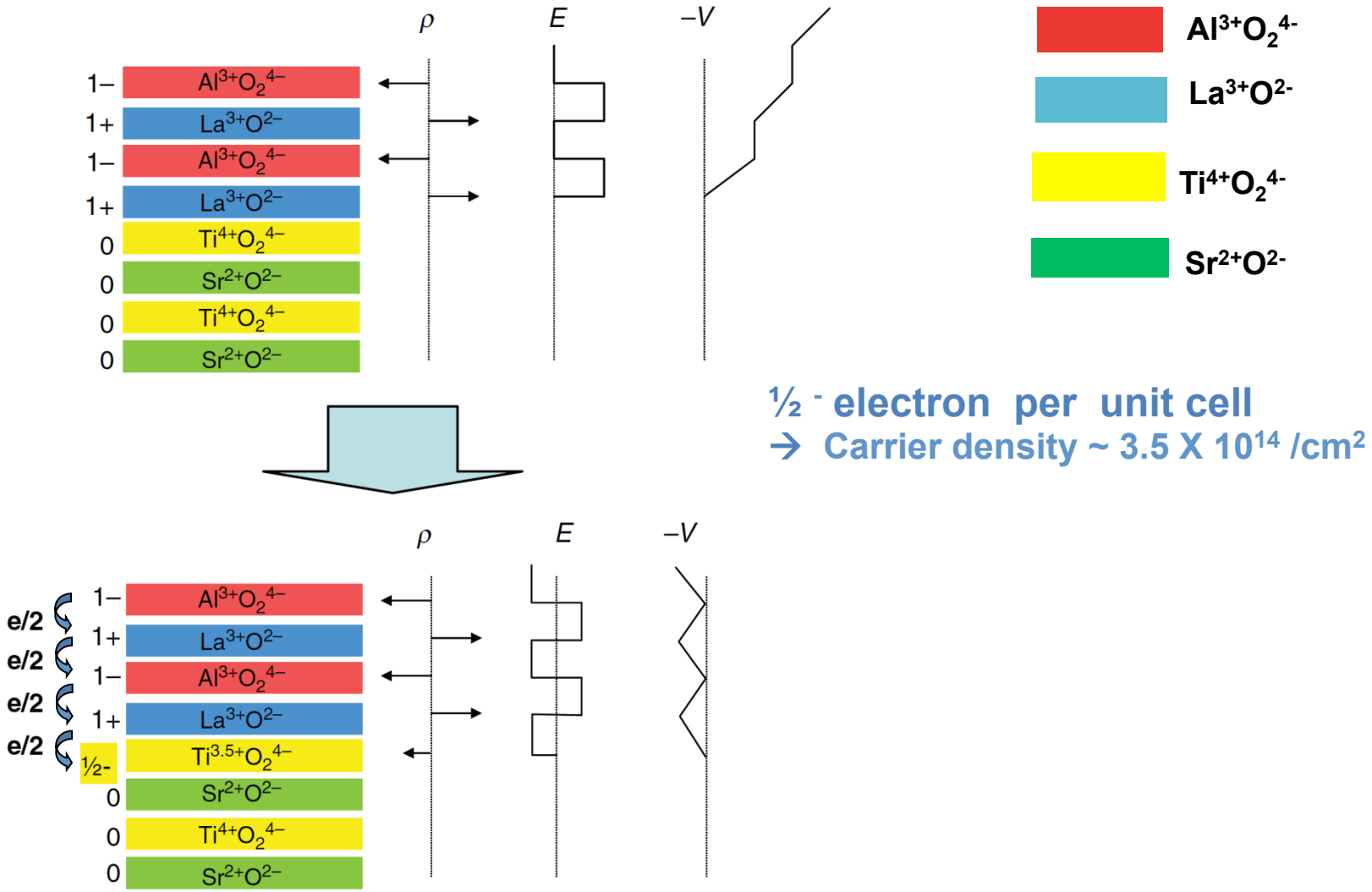




Seminal Papers by Hwang
Nature 2002 $LaTiO_3/SrTiO_3$
Nature 2004 $LaAlO_3/SrTiO_3$

Reyren et al. Science 2008

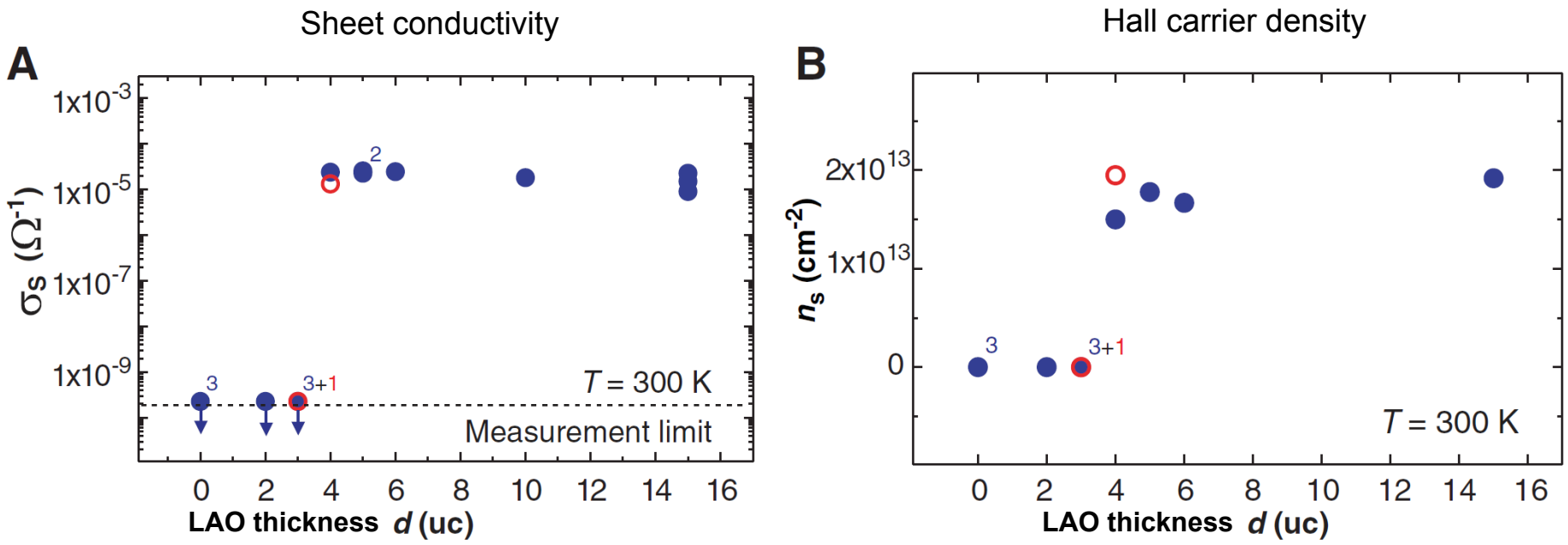
Polar catastrophe



Nakagawa, Hwang, Muller Nature Materials (2006)

Critical thickness for the conductivity

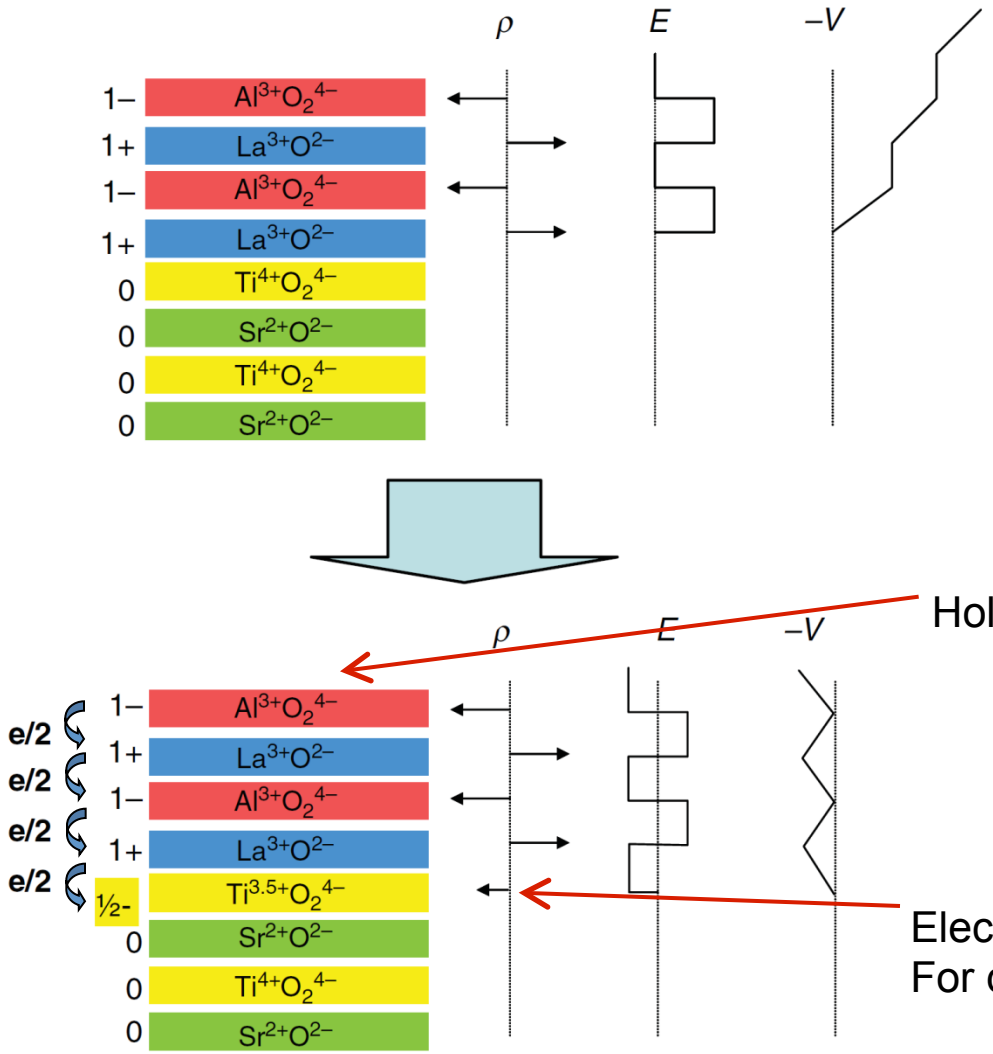
Sample grown at high Oxygen pressure ~ 10^{-4} torr



Conductivity really comes from the interface!

Thiel et al. *Science (2006)*

Magnetic moment in the ground state?

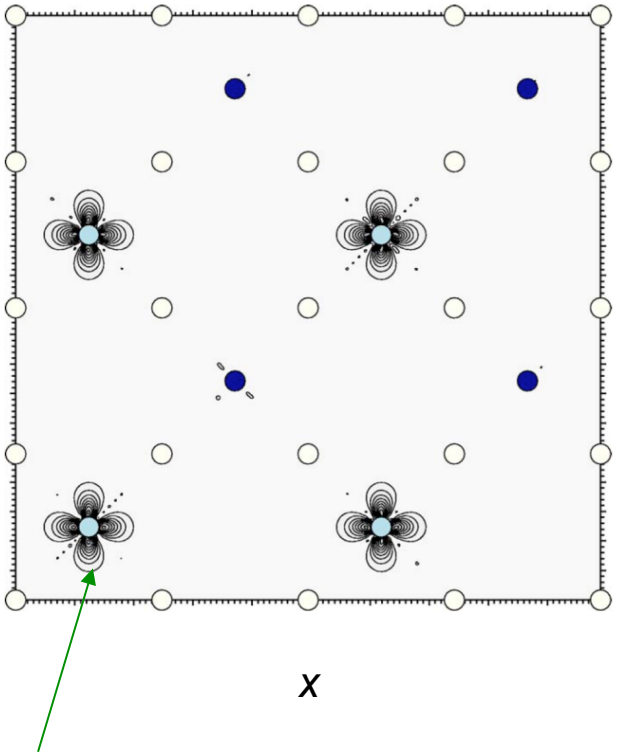


Holes on the surface, at O sites?

Electrons In Ti^{3+} orbitals
For d_{xy}, magnetic moment ~ μ_B / e

Strong correlation → magnetism?

$LaAlO_3/SrTiO_3$



Magnetization density at TiO_2 interface plane

Orbital polarization

Ferromagnet

2D magnetism from non-magnetic-materials

Pentcheva, Pickett PRB (2006)
Okamoto, Millis, Spaldin PRL (2006)

Challenge I : how to measure the magnetic moment of a single atom layer?

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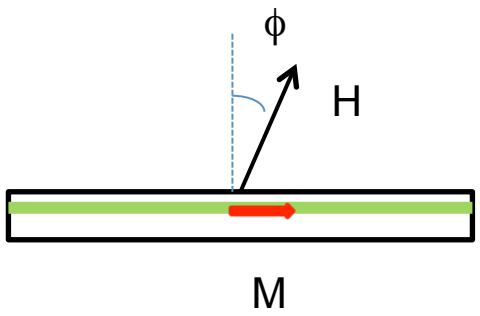


Torque on moment: $\tau = m \times B$

Torque magnetometry

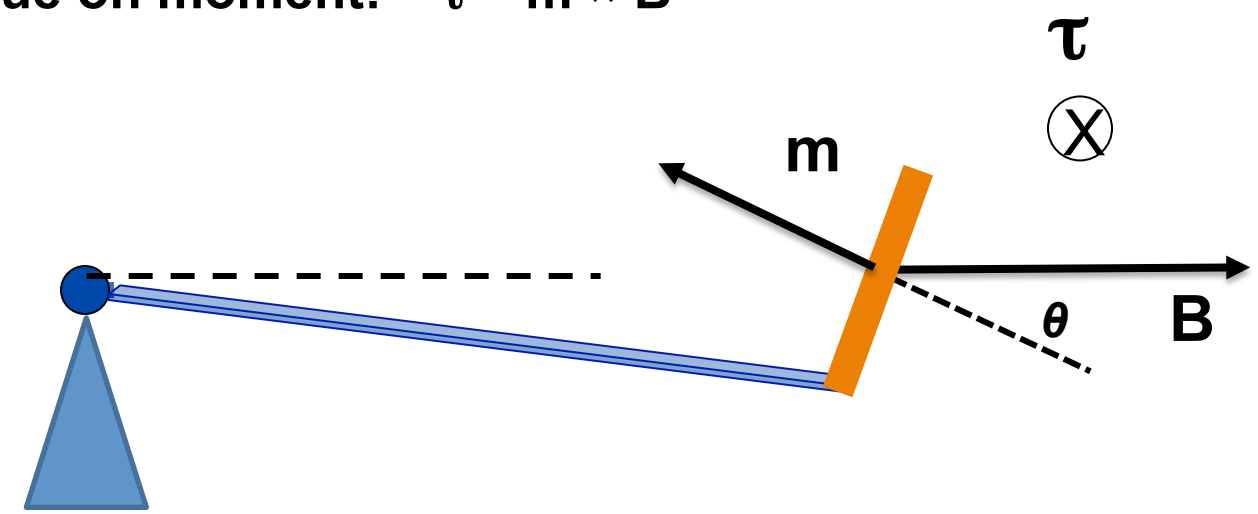
Torque on moment: $\tau = m \times B$

Deflection of cantilever: $\tau = k\,\varphi$

$$M_{eff} = \tau / \mu_0 HV\sin(\theta)$$

Torque magnetometry

Torque on moment: $\tau = m \times B$

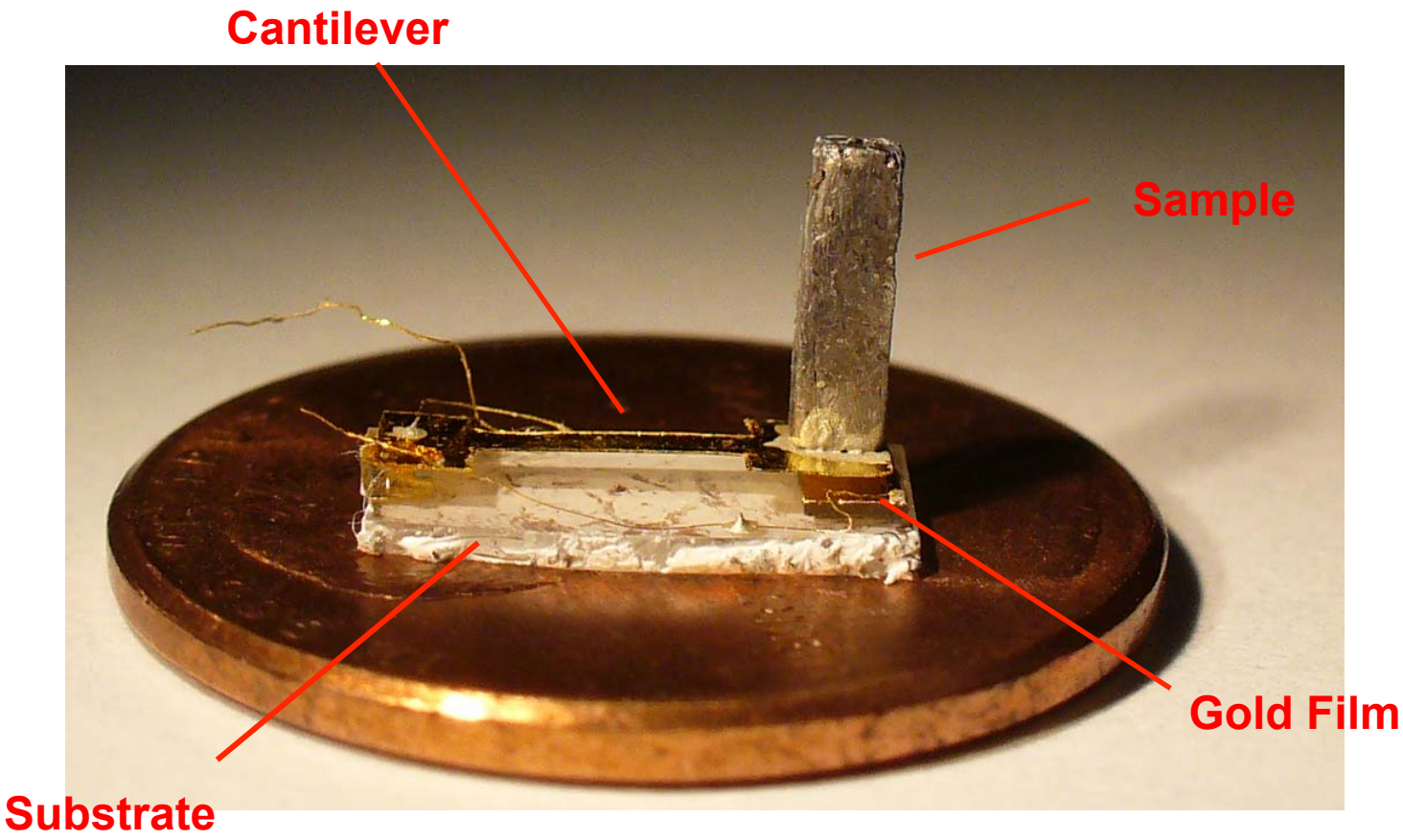


Deflection of cantilever → torque τ

$$M_{eff} = \tau / \mu_0 HV\sin(\theta)$$

Only sensitive to magnetic anisotropy

Cantilever setup of bismuth



1. Magnetic moment $\Delta m \sim 10^{-13}$ A.m^2 at 10 T
(SQUID MPMS, $\Delta m \sim 10^{-9}$ A.m^2)
2. Works up to 45 Tesla, at 20 m K ~ 300 K

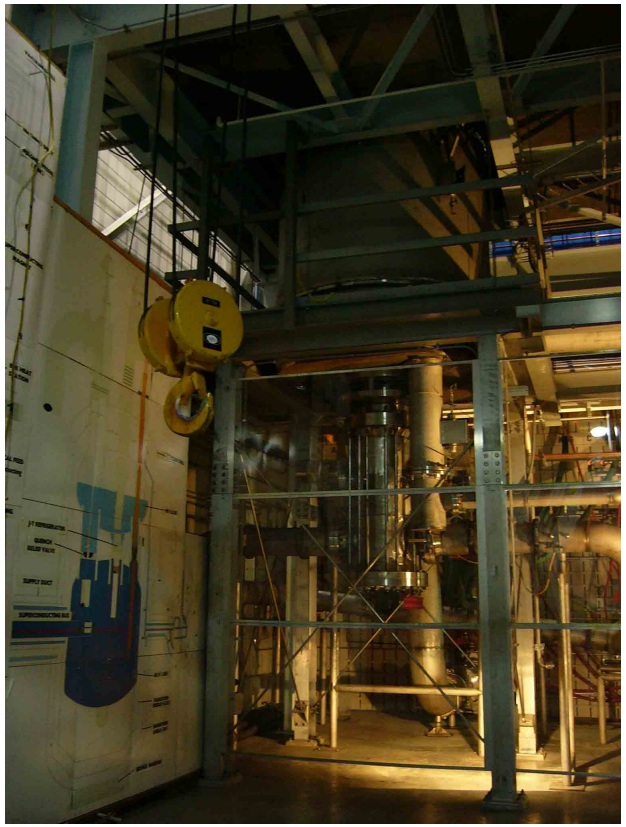
Li, Cava, Uher, Hebard, Ong ... Science (2008)

Laboratory

Dilution Refrigerator

18 mK – 40 K
Magnetic field up to 8 T

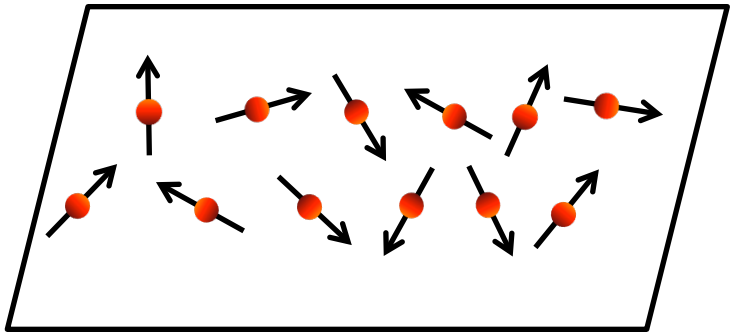
NHMFL Hybrid

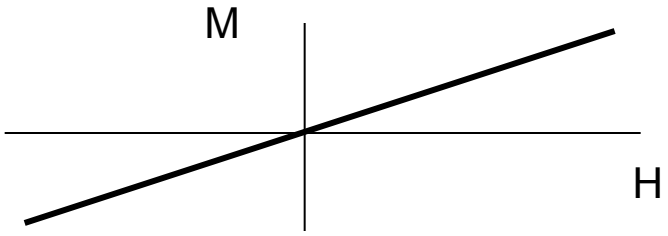


Magnetic field up to 45T

Torque curve examples

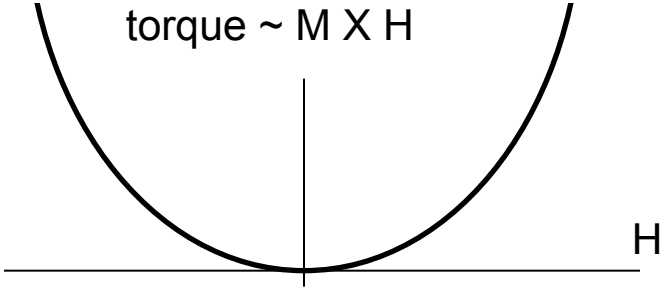
Paramagnet





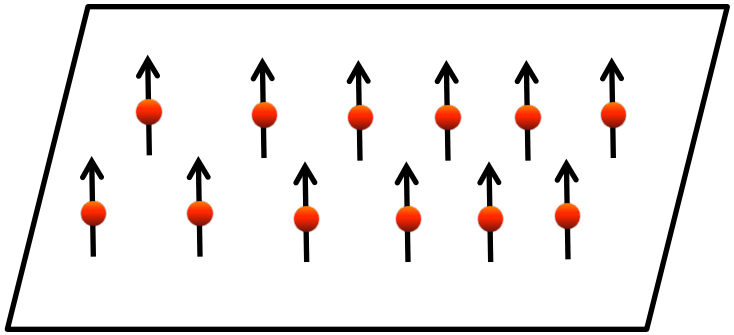
M proportional to H

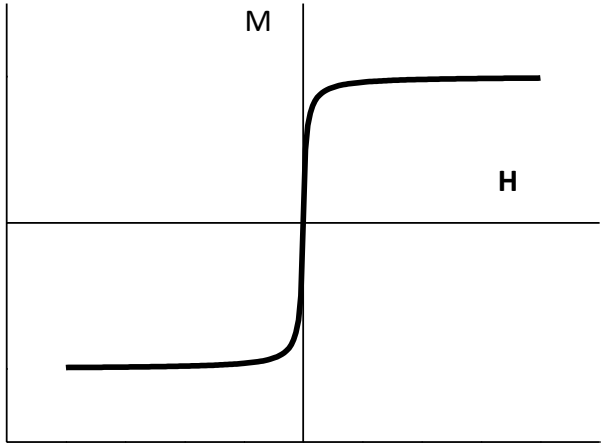
torque = M X H ~ H^2

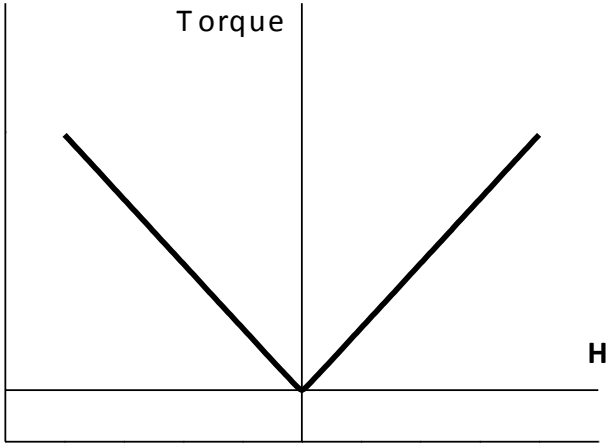


Torque curve examples

Soft Ferromagnet

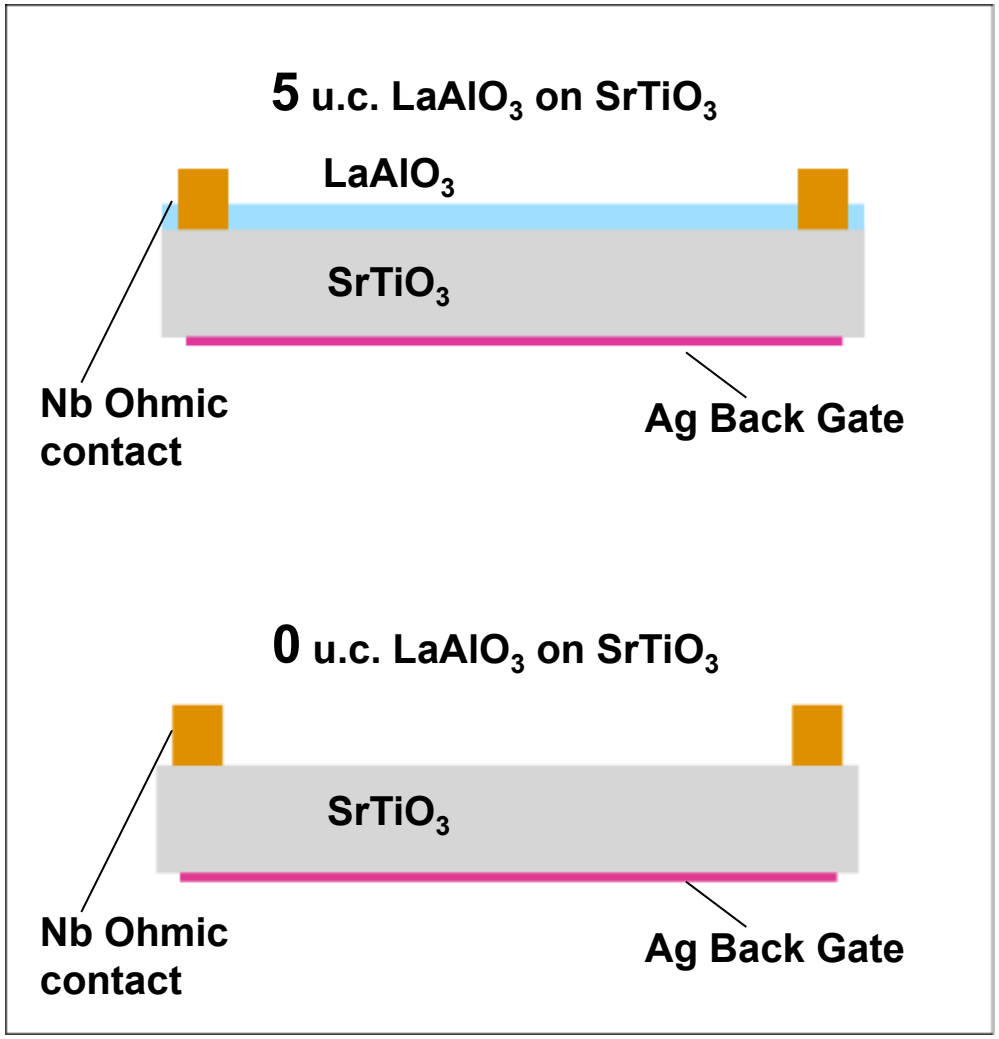




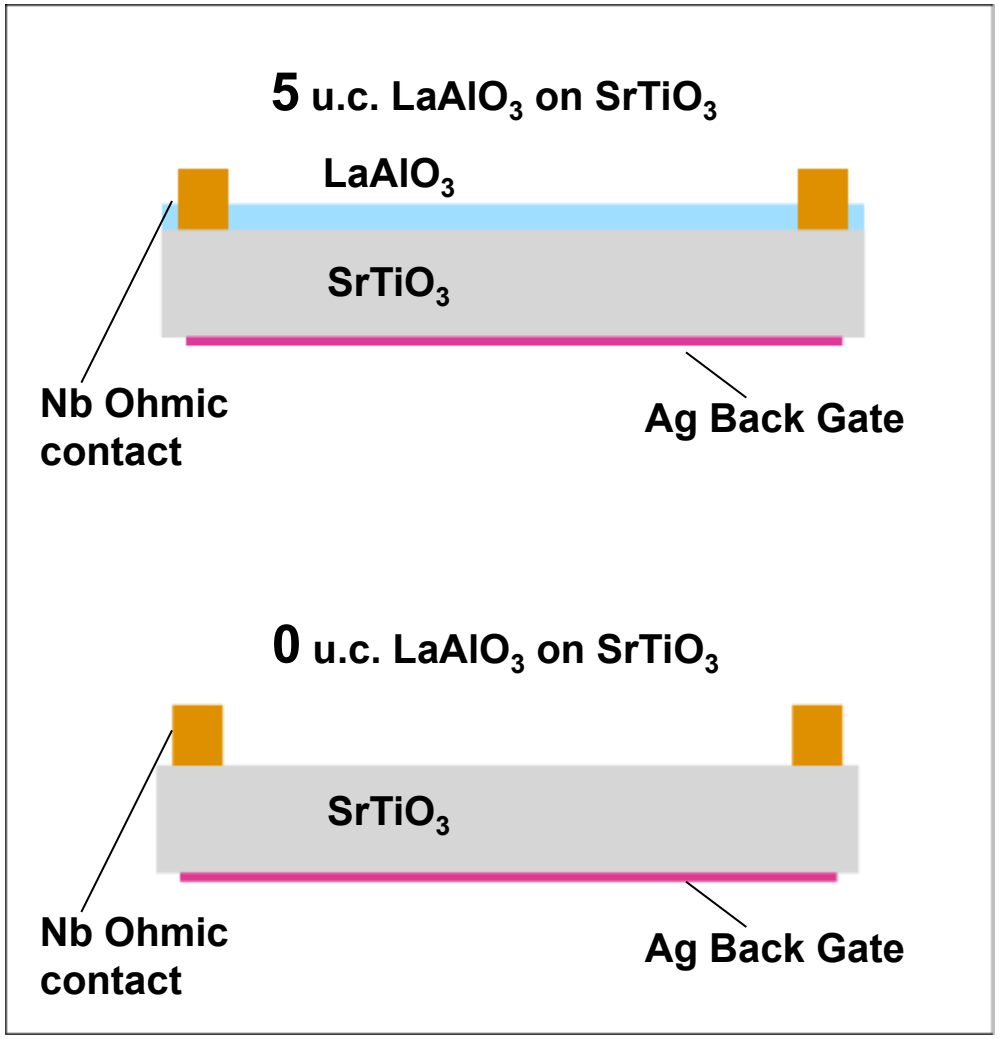


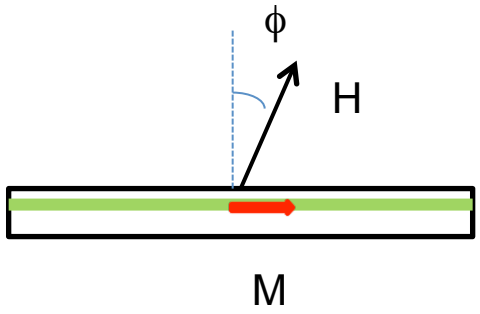
Challenge II : how to make sure the signal really comes from the interface?

Control experiments on $LaAlO_3/SrTiO_3$ interface

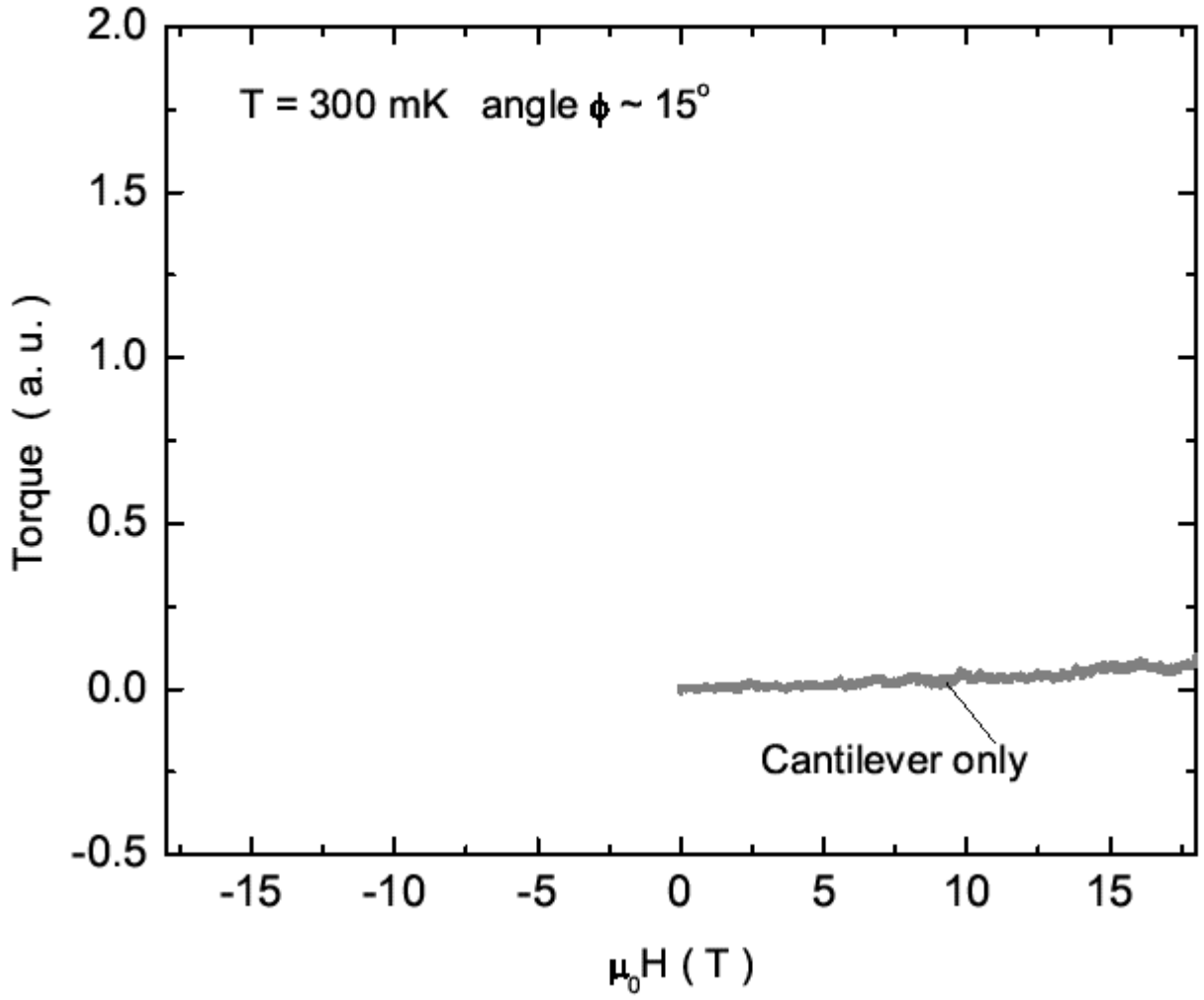


Control experiments on $LaAlO_3/SrTiO_3$ interface



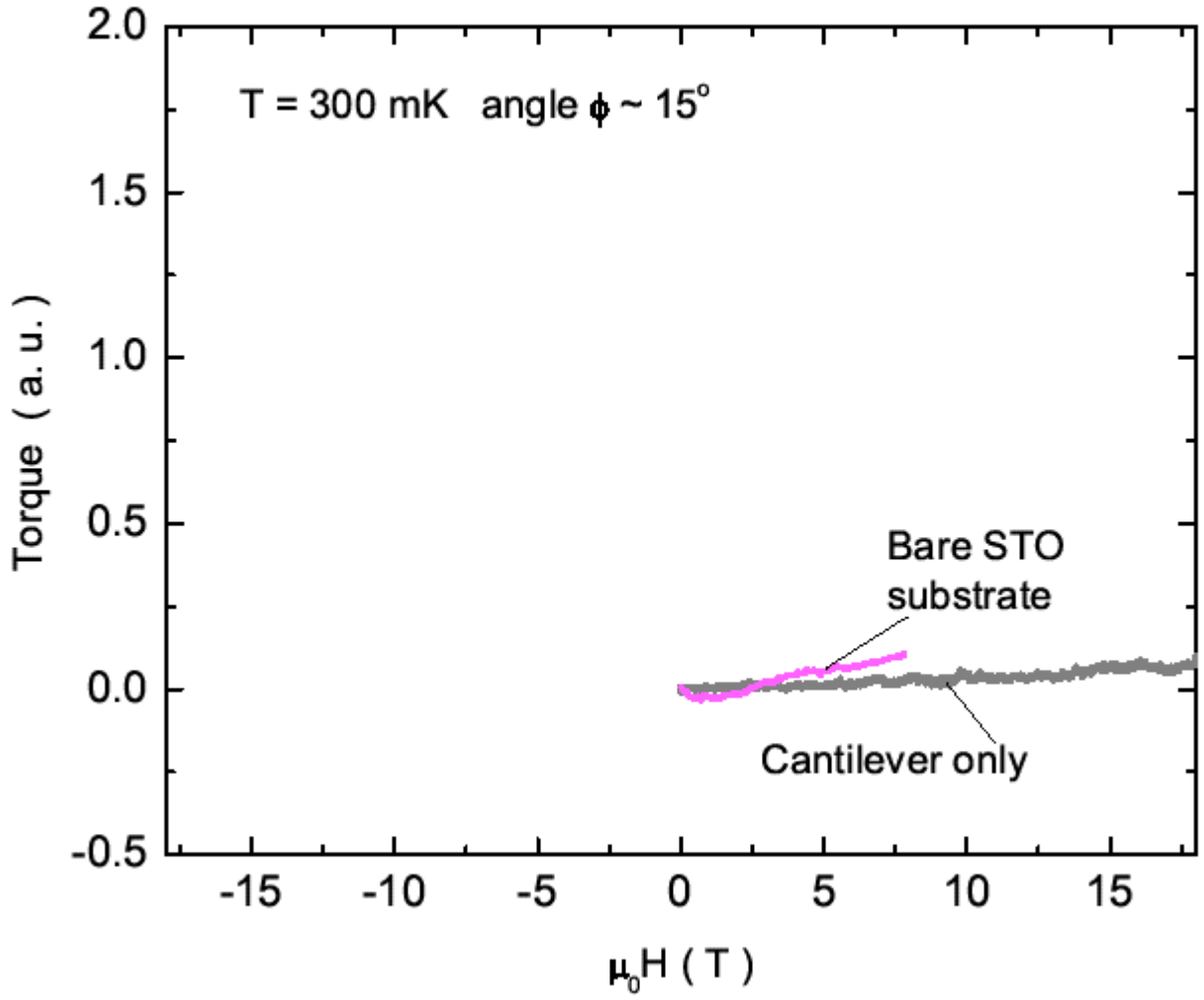


Tiny background signal from the cantilever



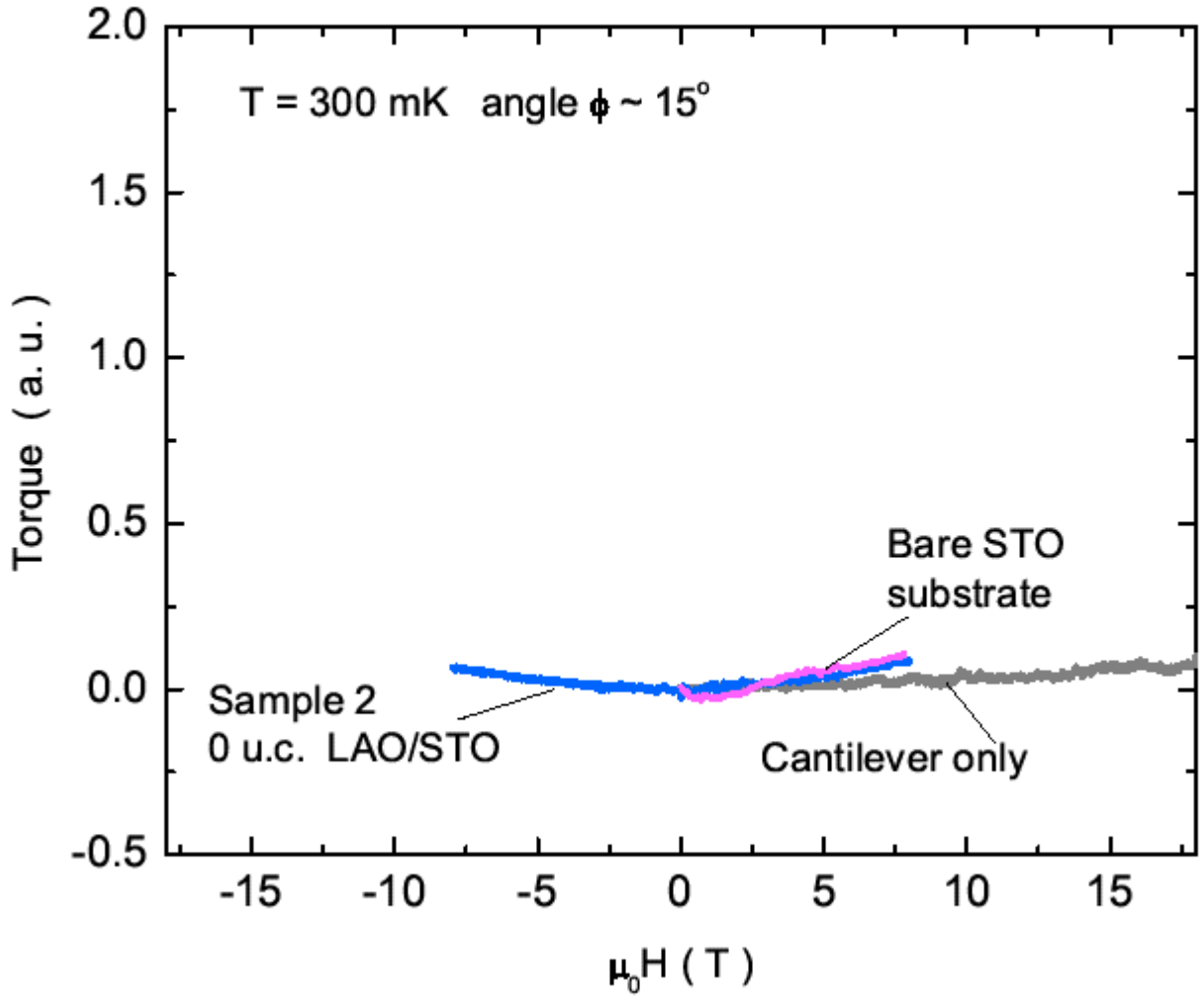
Li et al, Nature Physics 2011

Small background signal of STO substrate



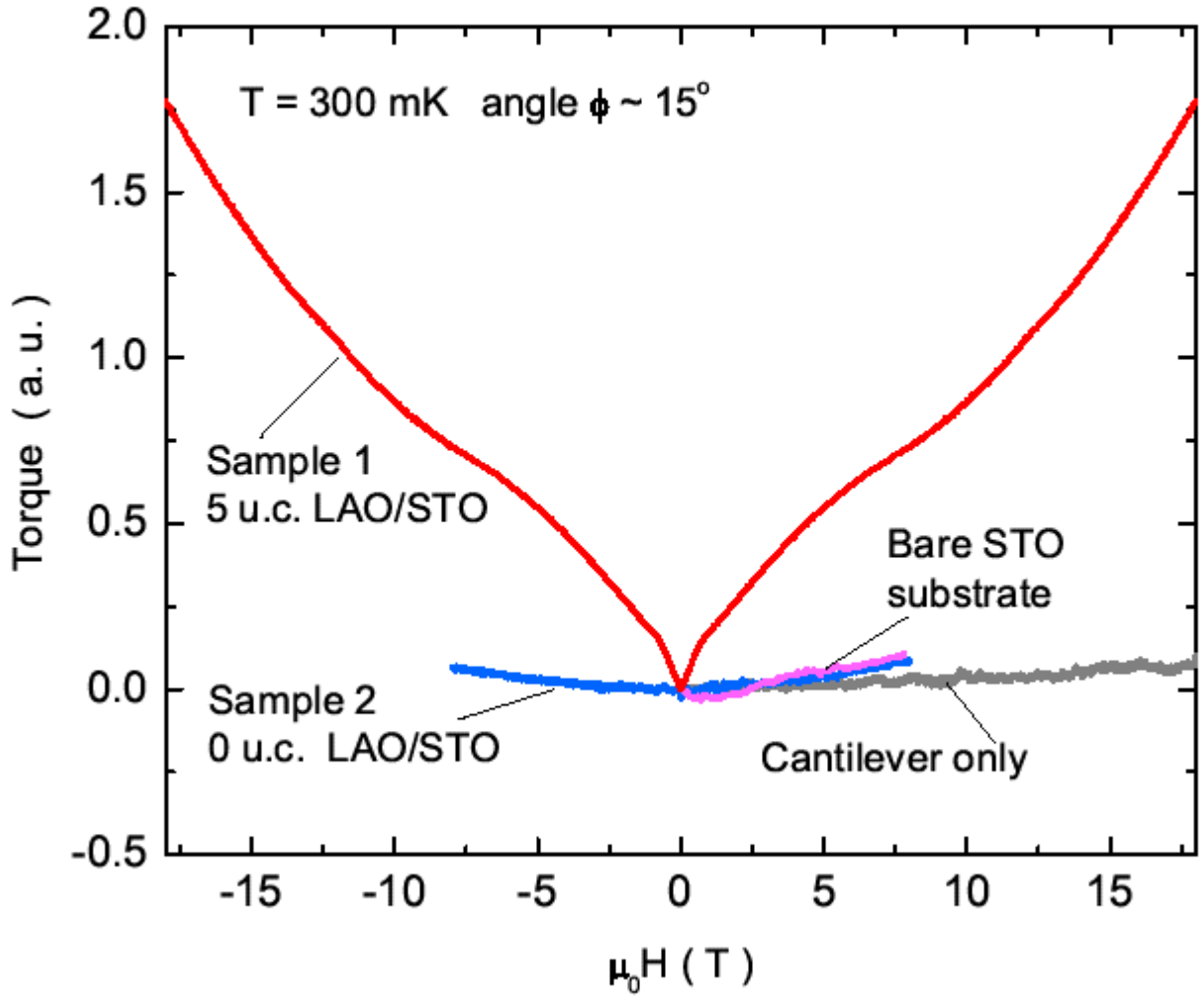
Li et al, Nature Physics 2011

Small torque signal of sample without $LaAlO_3$



Li et al, Nature Physics 2011

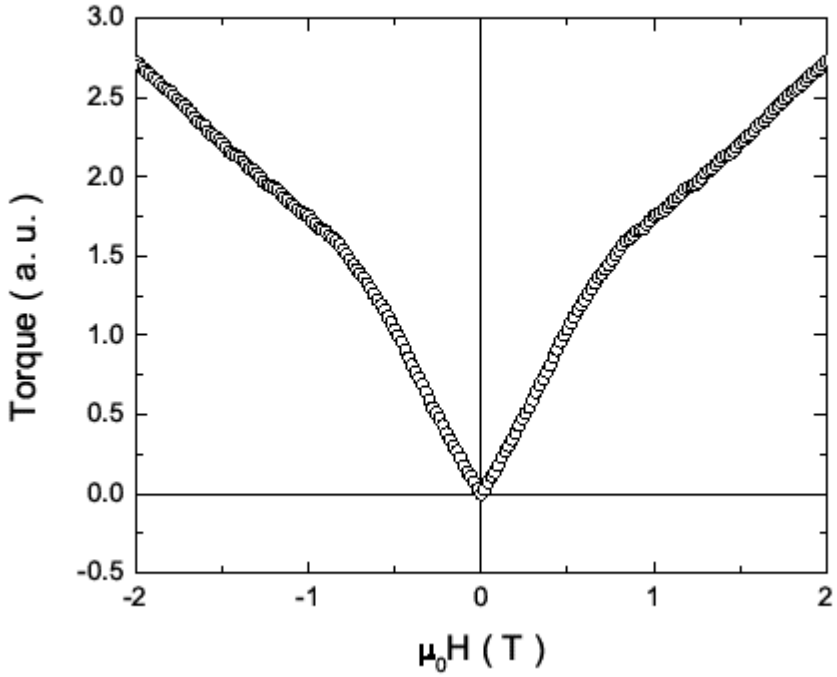
Large torque signal of sample with $LaAlO_3$

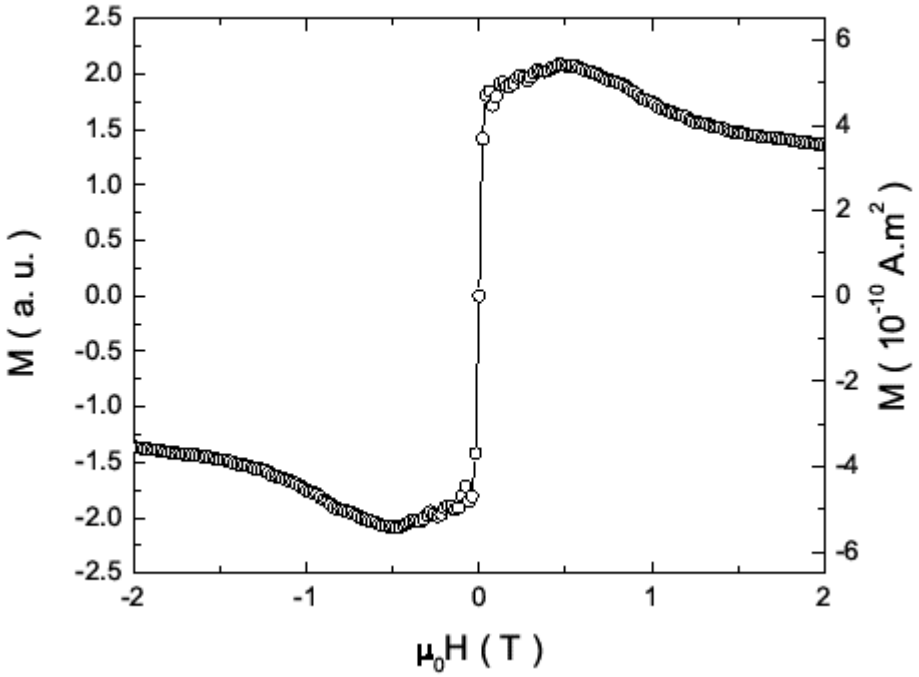


Li et al, Nature Physics 2011

Low field slope change in torque
→ Spontaneous magnetization

0.3 – 0.4 μ_B / u.c.

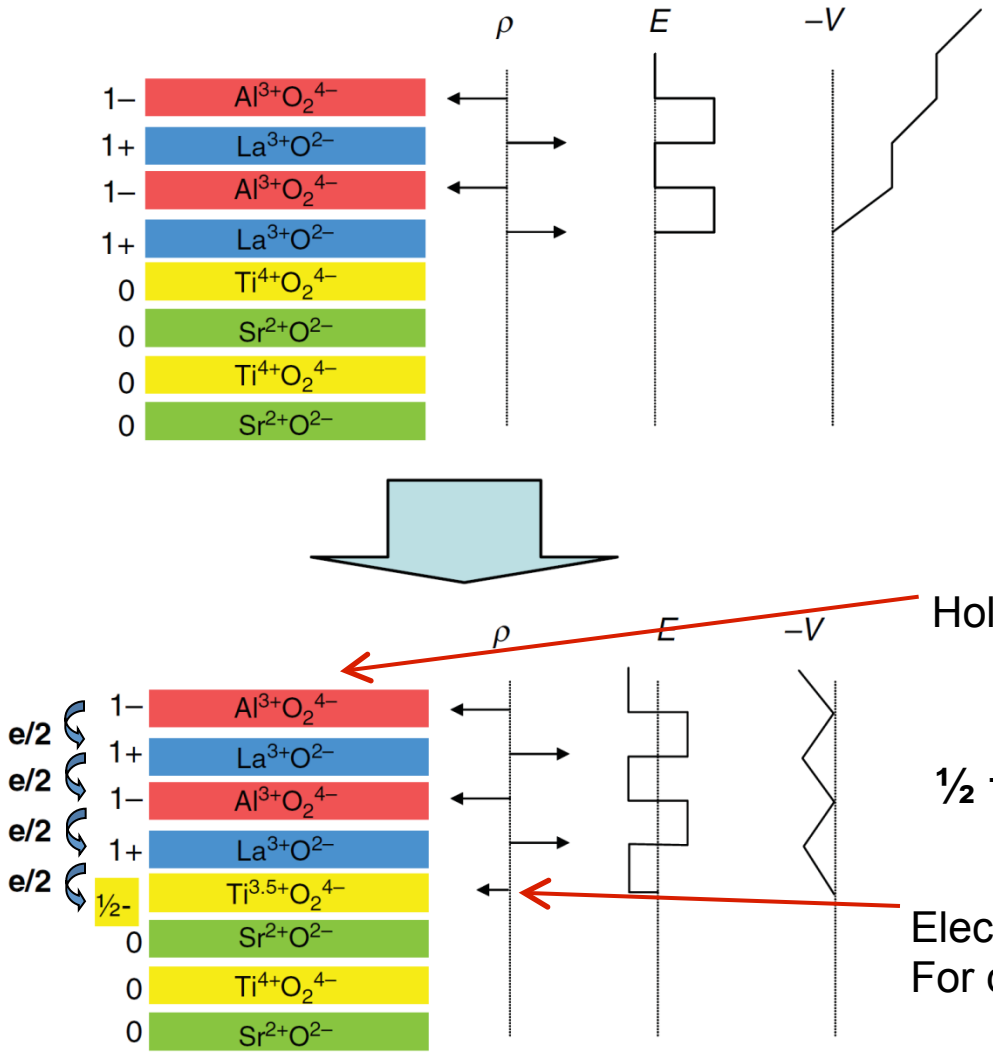




5 u.c. LAO/STO
T = 300 mK

Li et al, Nature Physics 2011

Origin of the magnetization?

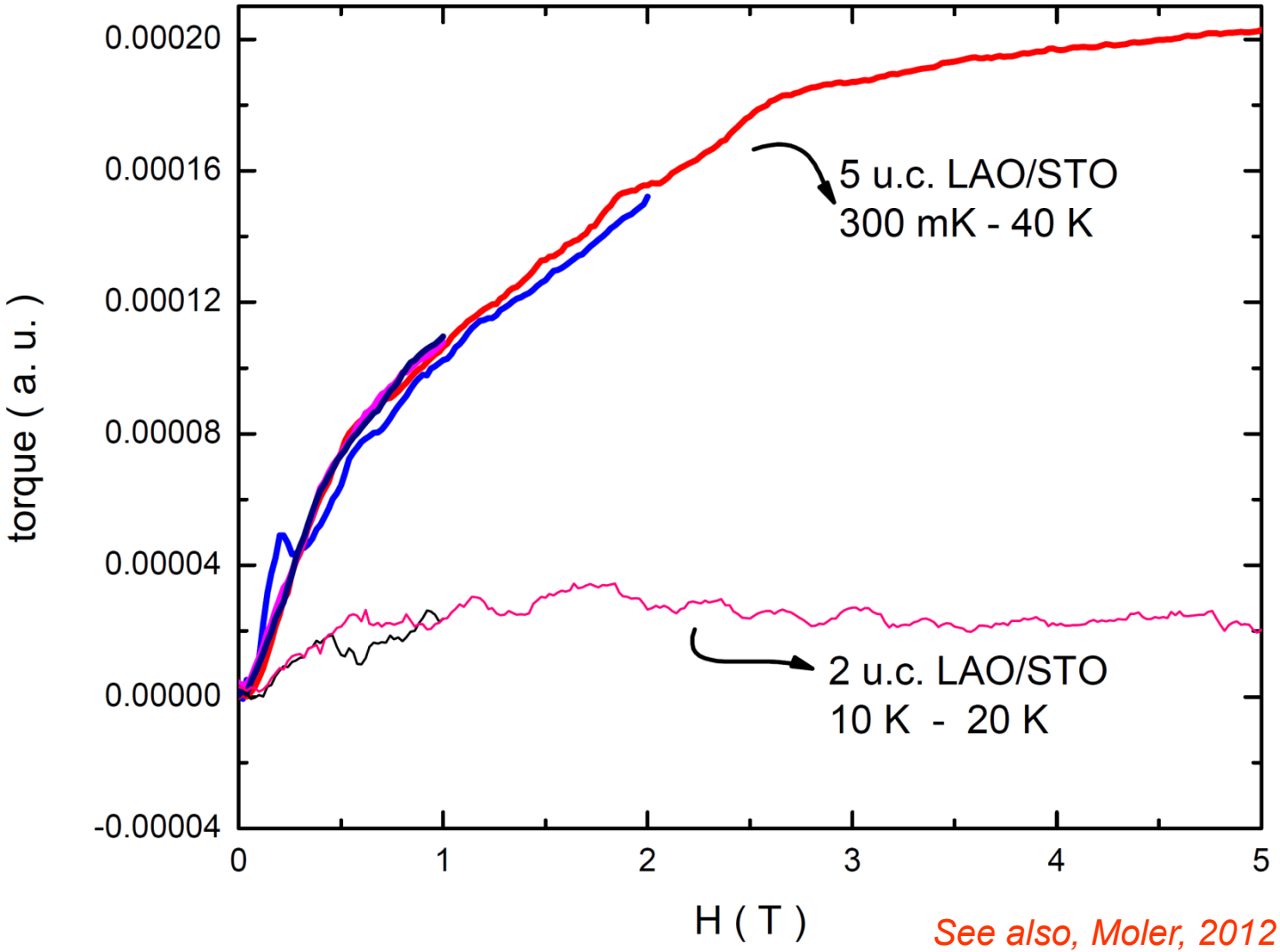


Holes on the surface, at O sites?

½ electron per unit cell

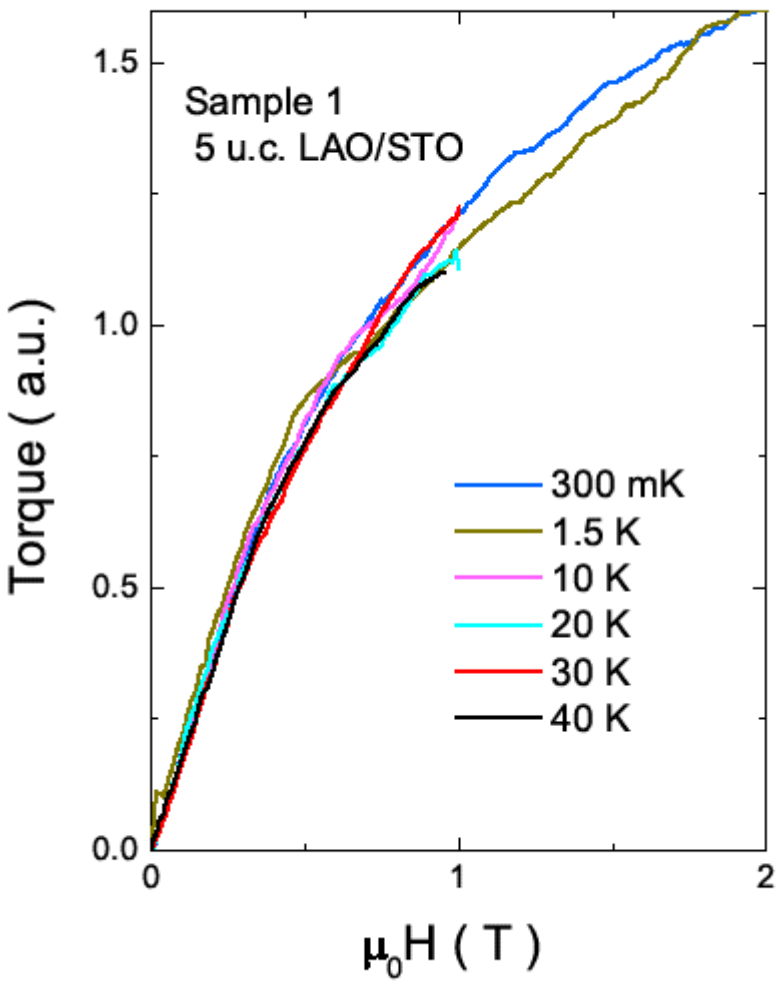
Electrons In Ti^{3+} orbitals
For d_{xy}, magnetic moment ~ μ_B / e

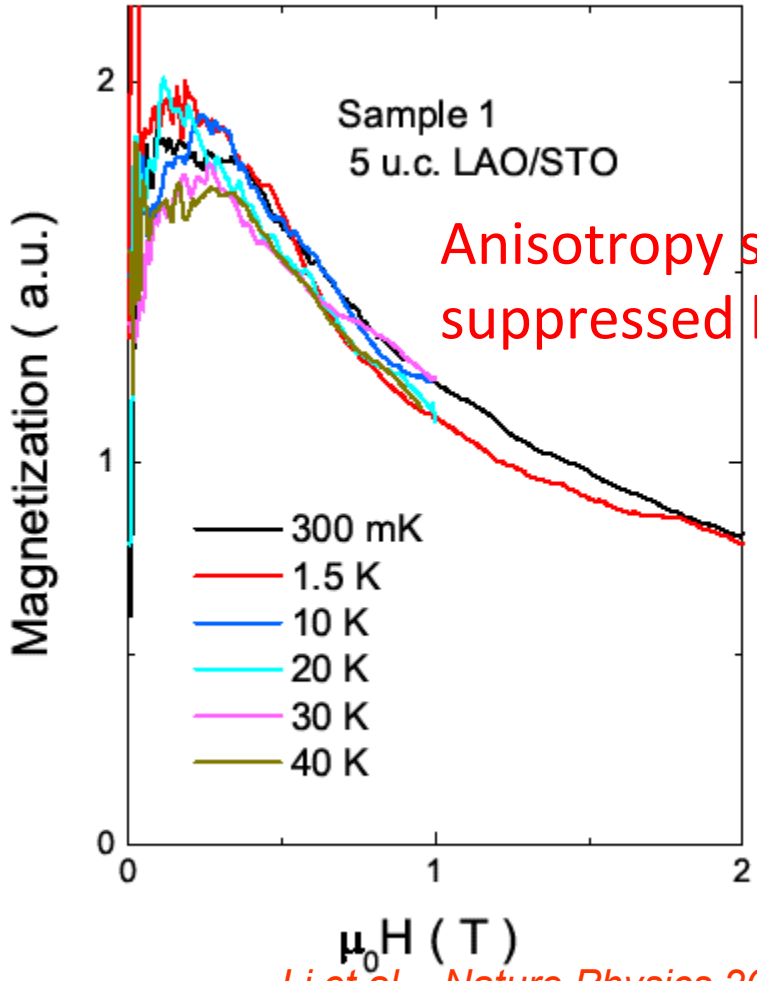
Critical thickness of magnetism



See also, Moler, 2012

Magnetization signal
NO big change up to 40 K

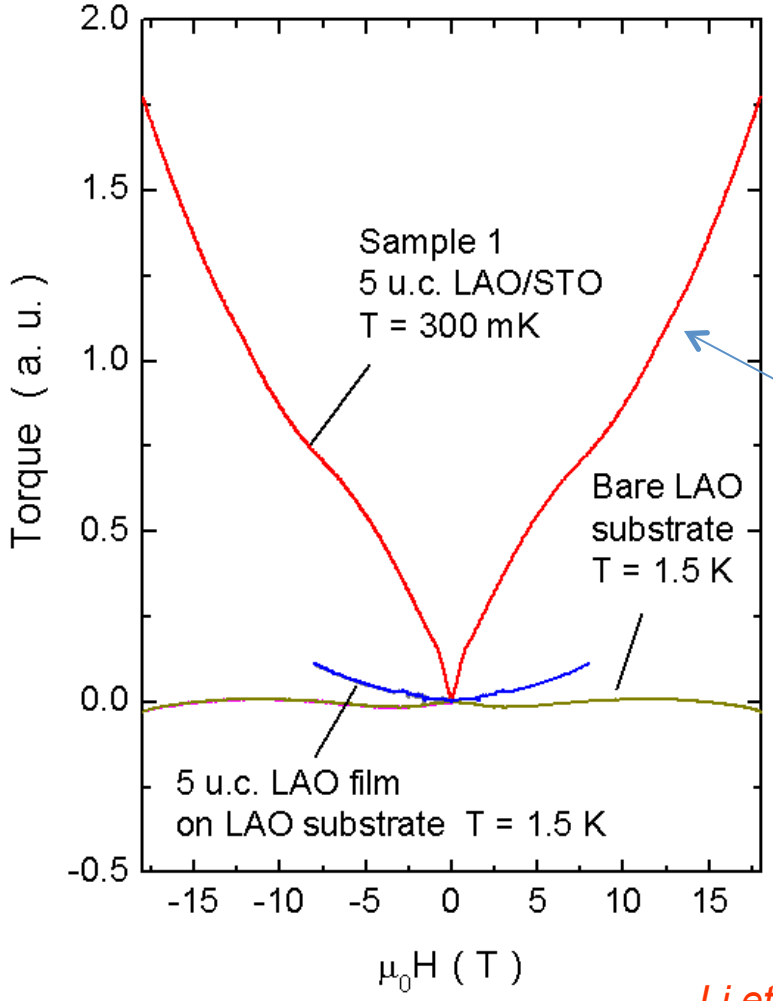




Anisotropy strongly suppressed by H_{perp}

Li et al, Nature Physics 2011

Other interface
LaAlO3 film on LaAlO3 substrate is non-magnetic

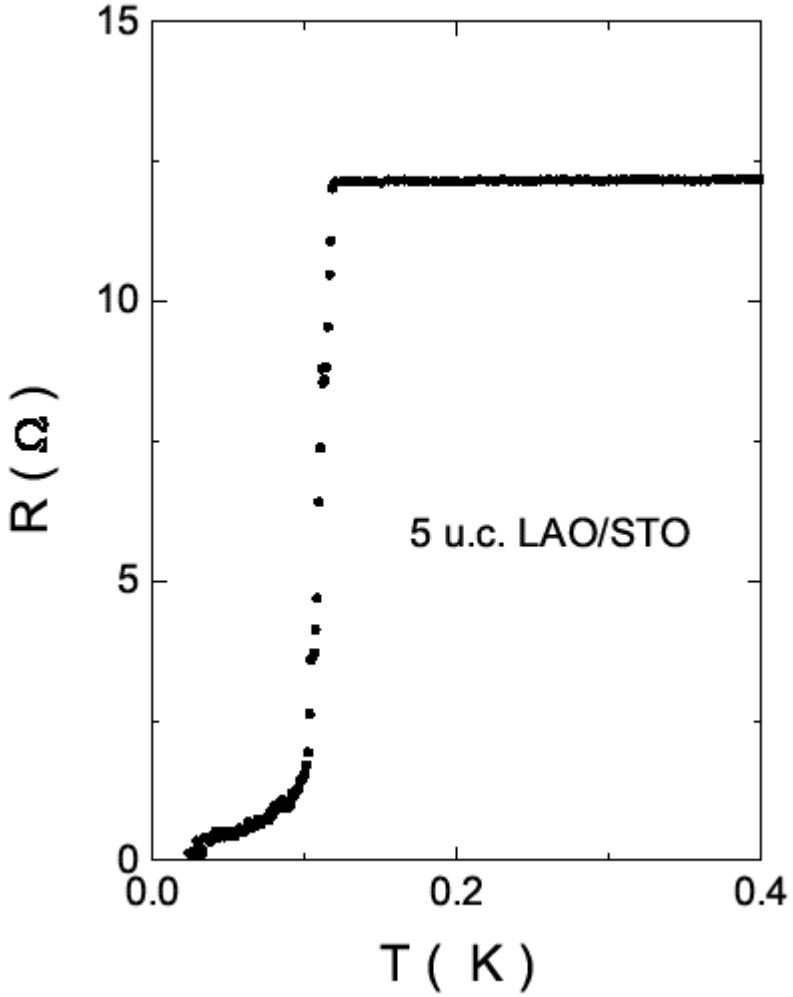


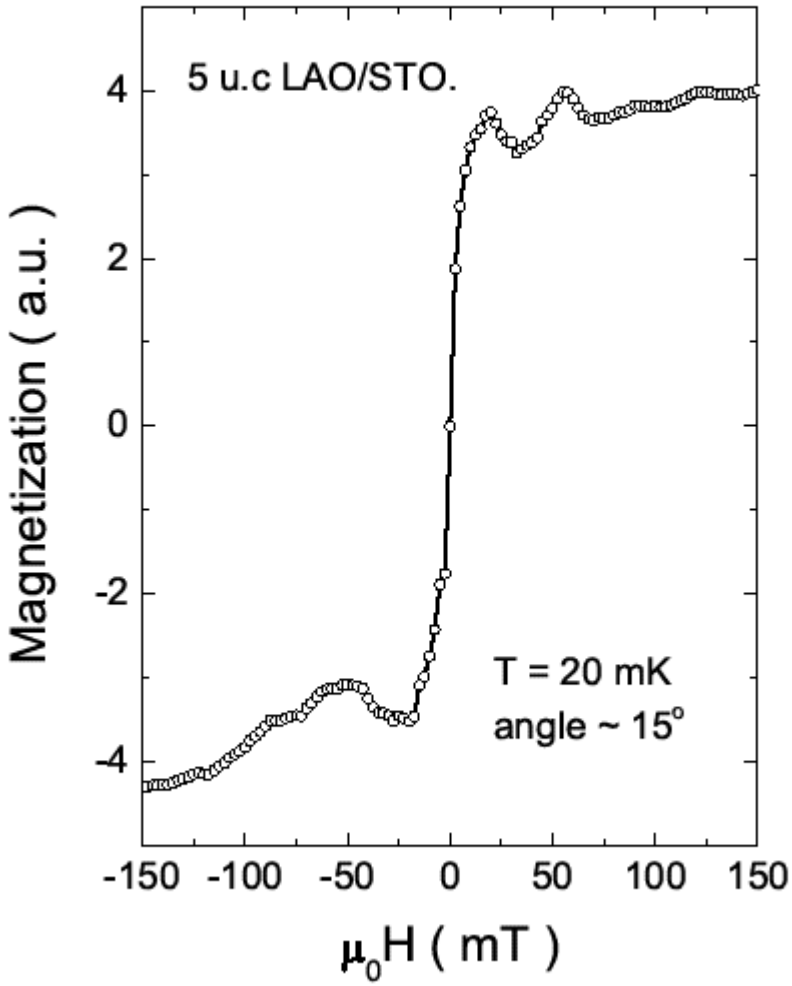
NOT from the disorder of the LAO film

Li et al, Nature Physics 2011

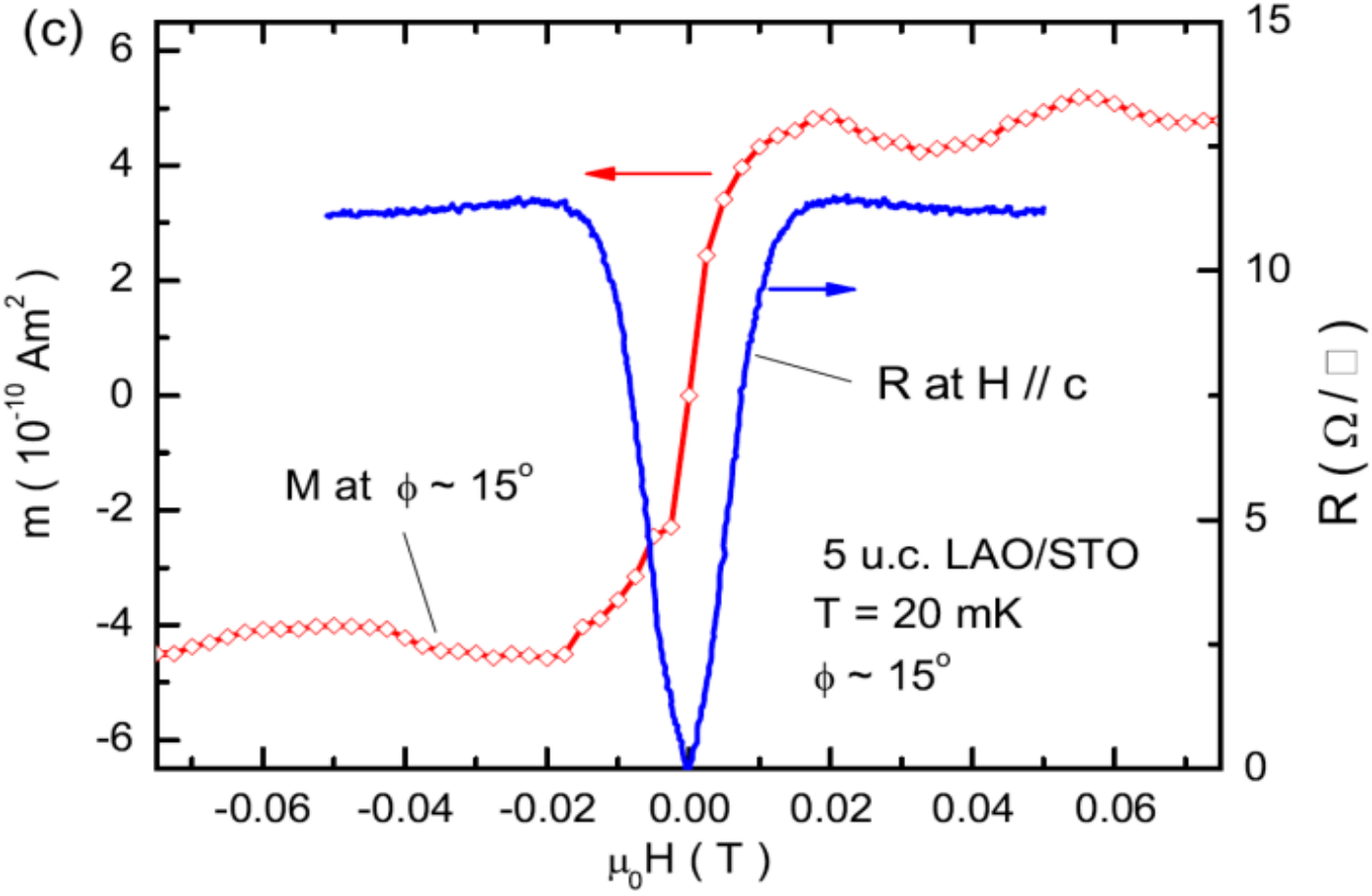
Coexistence of superconducting state and magnetic ordering

Superconducting T_c ~ 120 mK





Coexistence of superconducting state and magnetic ordering



Li et al, Nature Physics 2011

Other Evidence for Magnetism

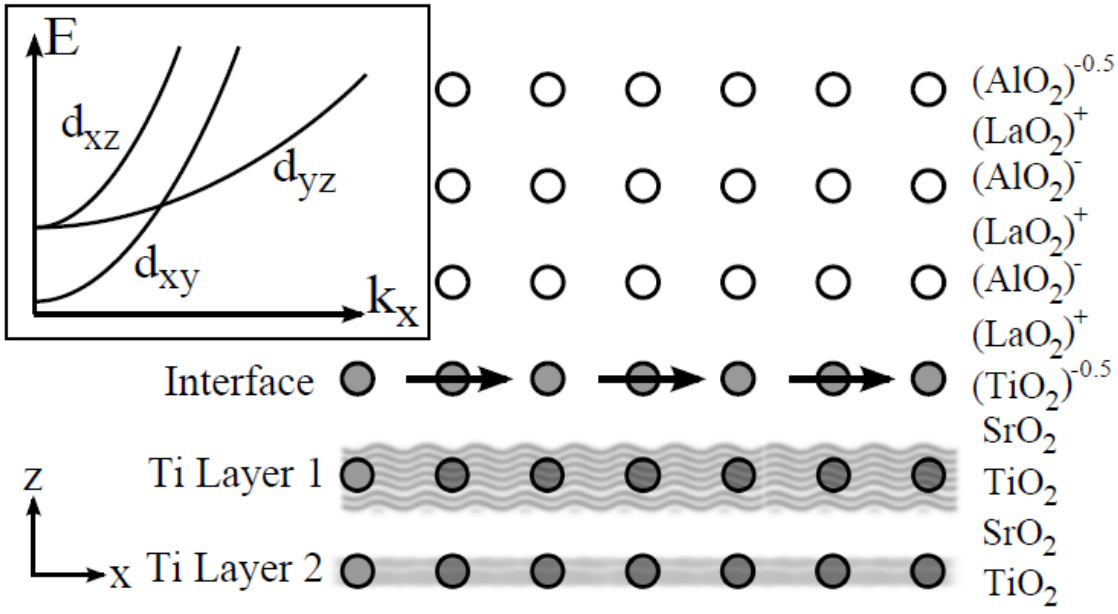
- **Scanning SQUID microscopy (Moller et al.)**
- **Hysteretic Magnetoresistance (Dikin et al.)**
- **Anomalous Hall effect (Ilani 2012)**

…

Possibility 1

Superconductivity and Ferromagnetism in Oxide Interface Structures: Possibility of Finite Momentum Pairing

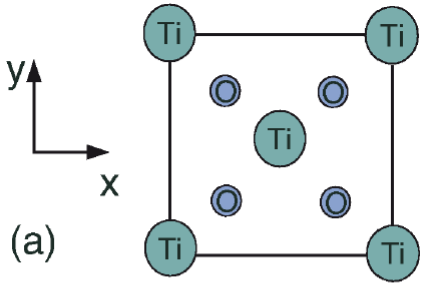
Karen Michaeli, Andrew C. Potter, and Patrick A Lee
Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

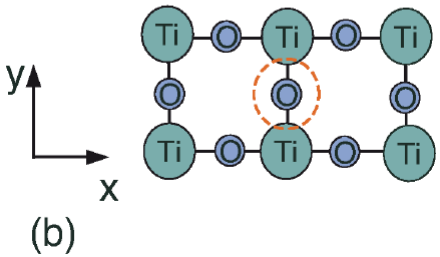


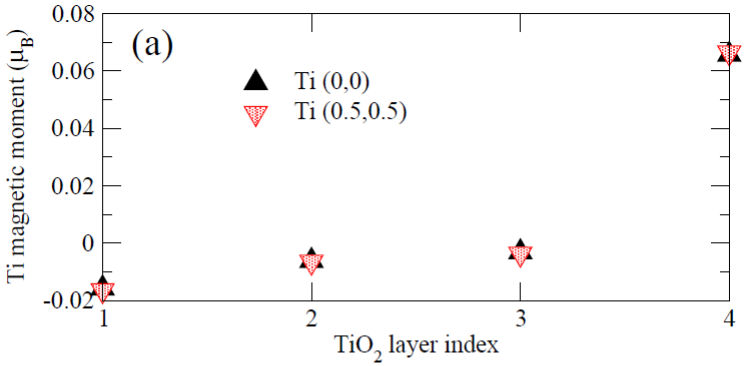
Possibility 2

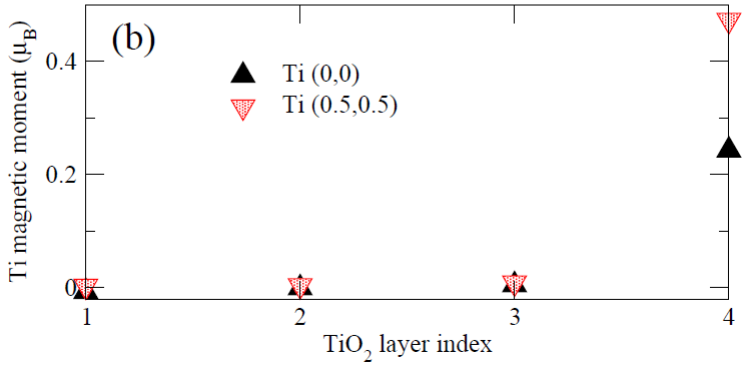
Magnetism and superconductivity at LAO/STO-interfaces both generated by the Ti 3*d* interface electrons?

N. Pavlenko[1], T. Kopp[2], E.Y. Tsymbal[3], G.A. Sawatzky[4], and J. Mannhart[2]
[1] *Institute for Condensed Matter Physics, 79011 Lviv, Ukraine,*
[2] *EKM and Institut für Physik, Universität Augsburg, 86135 Augsburg, Germany*
[3] *Department of Physics and Astronomy, Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, Nebraska 68588-0299, USA*
[4] *Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada V6T1Z1*
(Dated: May 9, 2011)









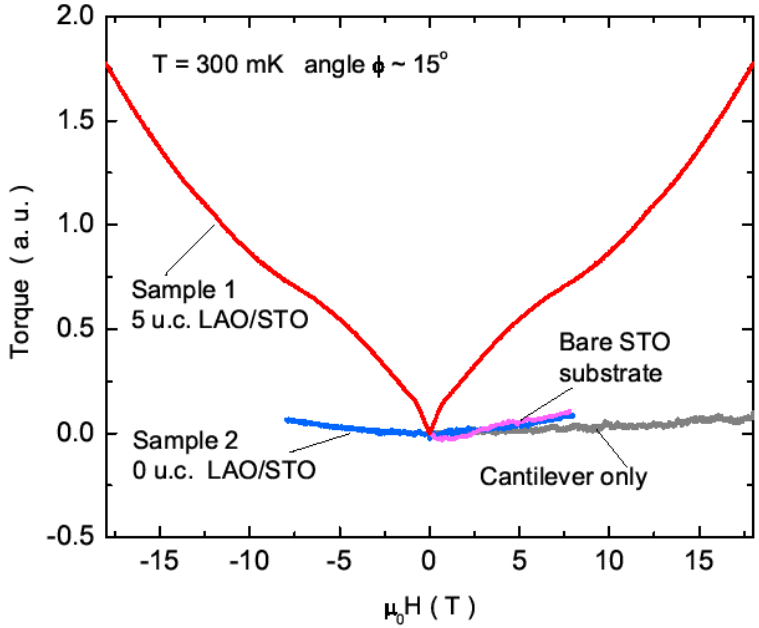
Other Possibilities

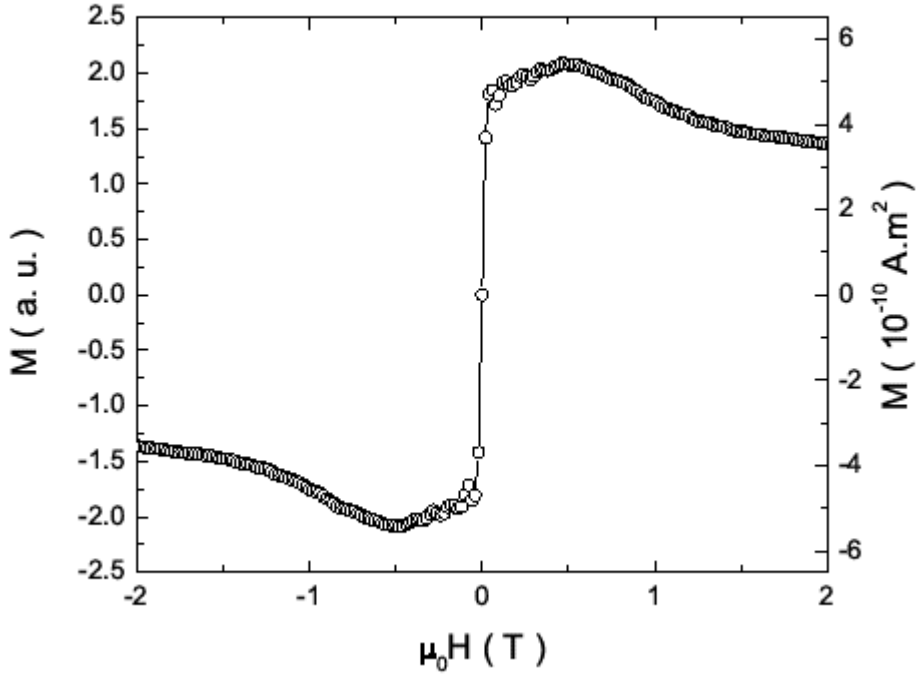
- **Itinerate Magnetism (Balents et al.)**

- **Hund Coupling and Spiral ordering (Randeria et al.)**

…

Conclusion
Two-dimensional magnetic system at $LaAlO_3/SrTiO_3$





- Detection of in-plane magnetic moment of single atom layer interface
- Coexistence of superconductivity and magnetism